Variations in Water Clarity and Bottom Albedo in Florida Bay from 1985 to 1997

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ABSTRACT: Following extensive seagrass die-offs of the late 1980s and early 1990s, Florida Bay reportedly had significant declines in water clarity due to turbidity and algal blooms. Scant information exists on the extent of the decline, as this bay was not investigated for water quality concerns before the die-offs and limited areas were sampled after the primary die-off. We use imagery from the Advanced Very High Resolution Radiometer (AVHRR) to examine water clarity in Florida Bay for the period 1985 to 1997. The AVHRR provides data on nominal water reflectance and estimated light attenuation, which are used here to describe turbidity conditions in the bay on a seasonal basis. In situ observations on changes in seagrass abundance within the bay, combined with the satellite data, provide additional insights into losses of seagrass. The imagery shows an extensive region to the west of Florida Bay having increased reflectance and light attenuation in both winter and summer begining in winter of 1988. These increases are consistent with a change from dense seagrass to sparse or negligible cover. Approximately 200 km² of these offshore seagrasses may have been lost during the primary die-off (1988 through 1991), significantly more than in the bay. The imagery shows the distribution and timing of increased turbidity that followed the die-offs in the northwestern regions of the bay, exemplified in Rankin Lake and Johnson Key Basin, and indicates that about 200 km² of dense seagrass may have been lost or severely degraded within the bay from the start of the die-off. The decline in water clarity has continued in the northwestern bay since 1991. The area west of the Everglades National Park boundaries has shown decreases in both winter turbidity and summer reflectances, suggestive of partial seagrass recovery. Areas of low reflectance associated with a major *Syringodium filiforme* seagrass meadow north of Marathon (Vaca Key, in the Florida Keys) appear to have expanded westward toward Big Pine Key, indicating changes in the bottom cover from before the die-off. The southern and eastern sections of the Bay have not shown significant changes in water clarity or bottom albedo throughout the entire time period.

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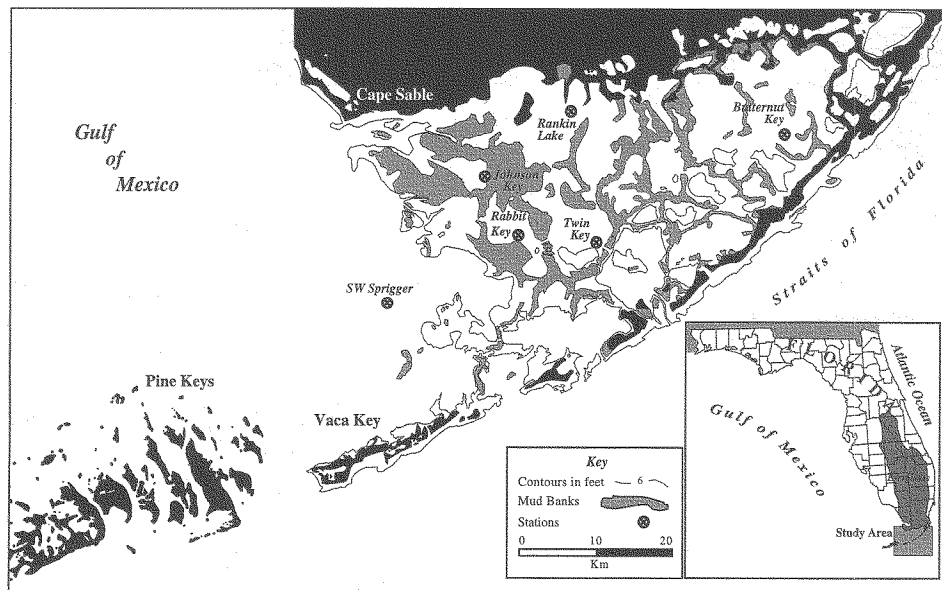
Fig. 1.   Location of stations described in the paper.

Introduction

Florida Bay, at the southern tip of Florida, United States (Fig. 1), has undergone dramatic environmental changes in recent years. Following major seagrass die-offs in the late 1980s, algal blooms and high turbidity (from resuspended sediments) have reportedly been more common in the bay. The initial seagrass die-off, which affected primarily *Thalassia testudinum* (turtle grass), has been linked to infection of *Thalassia* by the marine slime mold *Labyrinthula* sp., hypersalinity, and other physiological stresses (Robblee et al. 1991; Carlson et al. 1994; Durako and Kuss 1994). Prior to the die-off, water clarity was considered excellent, although few datasets exist to document this, and the widespread turbidity that is now observed was not reported. High turbidity and limited water clarity have been documented, particularly in the northwestern region of the Bay with the apparent increased sediment resuspension following the seagrass die-offs (Robblee et al. 1991; Fourqurean et al. 1993; Phlipps et al. 1995; Phlipps and Badylak 1996; Boyer et al. in press). Losses of other seagrasses, such as *Syringodium filiforme* (manatee grass) in the northwestern bay between 1984 and 1994 and *Halodule wrightii* (shoal grass) after 1992, may have resulted from reduced light availability ensuing from resuspension of sediments that had been stabilized by *Thalassia* (Phlipps et al. 1995; Stumpf and Frayer 1997; Hall et al. 1999).

The distribution of seagrasses in the region to the west of Florida Bay was documented in the late 1970s and early 1980s (Iverson and Bittaker 1986), but little is known about the subsequent condition of seagrass in this region offshore of Florida Bay. Because the bay was considered to be a viable, healthy, and undisturbed ecosystem prior to the die-offs, it was not the subject of water quality investigations. Starting in 1989, when severe water quality problems were observed within the boundaries of Everglades National Park, monitoring efforts concentrated on the portion of Florida Bay within the Park boundaries.

Previous modifications of the Everglades drainage have been blamed for hypersalinity in Florida Bay. Proposed restoration of the Everglades may result in further alteration of water flow into the bay (Boesch et al. 1993). Because of the potential impact of the restoration on the bay, several monitoring programs have been started to document current water quality and seagrass die-offs in the bay (Fourqurean et al. 1993; Tomas et al. In press; Boyer et al. 1997; Hall et al. 1999). Understanding changes in water clarity and seagrass distributions requires reference information on conditions in Everglades National Park, as well as conditions in adjacent areas, a task that could be accomplished with remote sensing techniques because of the availability of archival data.

This paper presents data collected by the Advanced Very High Resolution Radiometer (AVHRR) on water reflectance for the Florida Bay region over the 12-yr period from July 1985 to September 1997, and field data on light attenuation and changes in bottom cover. This combination of data allows us to interpret imagery in the context of current conditions, providing the first quanti-

tative information on changes in the region prior to the die-offs.

Methods

SATELLITE IMAGERY

The Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration's polar-orbiting meteorological satellites has provided almost daily imagery at a 1-km pixel size for over 15 yr. In oceanography, the sensor has had primary importance for collecting data on sea-surface temperature. While the visible bands on the instrument were designed for cloud and land studies, they have shown value in the study of turbid coastal water (Stumpf and Pennock 1989, 1991; Stumpf et al. 1993; Gower 1994; Walker 1996; Gould and Arnone 1997). The AVHRR generates a continuous, high-frequency record which means that it is currently the best instrument for documenting changes in water clarity within large estuaries. (In contrast, the Landsat sensors, while offering 25 yr of coverage at 80 m and less pixel size, have an approximately 2-wk repeat, giving only 40–50 usable images for Florida Bay.)

The AVHRR collects data in two reflected-light bands: channel 1 in the red at 580–680 nm and channel 2 in the near-infrared at 720–1,000 nm. The red band is suitable for investigating turbid coastal waters and, fortuitously, has less sensitivity to dissolved pigments or chlorophyll than shorter wavelengths (blue and green). The near-infrared band is used primarily for correction of atmospheric aerosols, the major contaminant in the signal.

The dataset used here extends from July 1985 to September 1997. Sources of data include the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center, the Louisiana State University's Earth Scan Lab, and the University of South Florida (USF) through the USF-Florida Department of Environmental Protection (FDEP) Joint-Use Facility. Nearly 1,700 scenes are used from over 2,000 scenes processed, with about 1,000 nominally cloud-free scenes (Fig. 2). The analysis uses the afternoon satellites, NOAA-9, NOAA-11, and NOAA-14, as these have the best relative calibration and provide more robust datasets during winter, when the sun is lowest. The failure of NOAA-13 upon launch in 1993, left the aging NOAA-11 as the primary satellite in 1994. The orbit of NOAA-11 had precessed to late afternoon, precluding quality imagery in winter 1994 because of the low sun angles. NOAA-11 failed in September 1994, and an afternoon satellite was not available until the launch of NOAA-14 in late December.
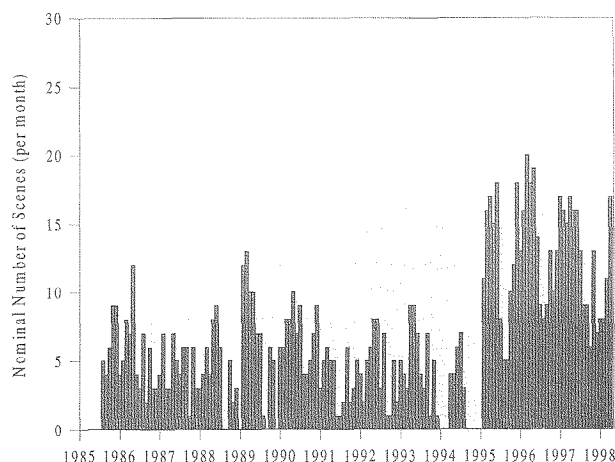

Fig. 2. Nominal number of scenes per month, based on cloud-free pixels. Nominal scenes are determined from the total number of cloud-free pixels in the bay during the month divided by the number of pixels that comprise the bay. For example, four scenes, each with 75% cloud-cover, result in three nominal scenes.

While each AVHRR sensor is calibrated before launch, the lack of onboard calibration for reflected light has previously raised concerns for post-launch calibration and sensor deterioration. This problem was resolved when a relative calibration of the sensors on the afternoon satellites was developed by the NOAA-NASA Pathfinder program. The Pathfinder program uses sites in low-latitude deserts having minimal moisture or seasonal change to provide relative calibration between satellites and to correct for degradation (Rao and Chen 1995, 1996). Absolute calibrations have been examined through determination of the absolute calibration at a particular time against aircraft-based sensor (e.g., Abel and Guenther 1993). This paper uses the intersatellite and intrasatellite calibration of Rao and Chen (1995, 1996) as applied in Stumpf and Frayer (1997), with the exception that for NOAA-14, we have reverted to the linear degradation model of Rao and Chen (1996). The calibration provides radiance in each band.

The reflectance of the water (R_w), which includes the bottom where the water is optically shallow, is determined by

$$R_w = \frac{\pi L_w(\lambda)}{E_d(\lambda)} \tag{1}$$

where L_w is the water-leaving radiance, E_d is the downwelling irradiance entering the water, and λ is the spectral band. L_w and R_w refer to values above the water surface. R_w is approximated by R_d, which is the Rayleigh and aerosol corrected channel 1 reflectance:

$$R_d = R_c(\lambda_1) - YR_c(\lambda_2) \tag{2}$$

with subscripts 1 and 2 denoting channels 1 and 2 and:

$$R_c(\lambda) = \frac{\pi L_*(\lambda)/E_0(\lambda) - \pi L_r(\lambda)/E_0(\lambda)}{(1/r^2)\,T_0(\lambda)\,T_1(\lambda)\cos\theta_0} \quad (3)$$

where L_* is the radiance measured at the satellite, L_r is the Rayleigh radiance, E_0 is the solar constant, r is the normalized earth-sun distance, θ_0 is the solar zenith angle, and T_0 and T_1 are the transmission coefficients for sun-to-earth and earth-to-satellite respectively. This model follows that used for CZCS (Gordon et al. 1983) and is described in more detail in Stumpf and Frayer (1997) and Stumpf (1992). The datasets were mapped to a Mercator projection with a pixel size of 1.13 km at latitude 25°N and residual navigational errors were removed by registering the image within a pixel of the NOAA digital shoreline. The Gulf Stream site showed a slight trend of decreasing reflectance over the 12 yr, suggesting a systematic bias to greater offsets with earlier scenes. Monthly average image values (discussed below) were corrected month-by-month for this bias (Stumpf et al. 1997). In addition to reflectance calculations, cloud-contaminated pixels were flagged using a combination of techniques: thresholds on sea-surface temperature and channel 2, and spatial variations on channel 2 and a thermal band.

In our dataset the typical month has 3–9 nominally cloud-free scenes prior to 1994 and 8–16 scenes starting in 1995 (Fig. 2). Winter 1994 had only four acceptable scenes owing to the extremely late overpass time of NOAA-11 (about 1600 local standard time; scenes with solar zenith angles > 70° were discarded). Gaps occur in late summer months in our coverage for 1988–1989; readers should avoid overinterpreting summary data for these summers. From the available images, we determined monthly average images using the cloud-free pixels, then determined the mean winter reflectance from December to March (e.g., winter 1986 corresponds to the period December 1985 to March 1996), and the mean summer reflectance from June to September.

Most of Florida Bay is shallow (< 2 m). Because of the shallow and highly variable bathymetry, which has not been surveyed in over 100 yr, corrections for bottom reflectance in the imagery are problematic. In winter, the high sediment load tends to result in an optically-deep water column. During the summer, the generally clearer water results in the bottom reflectance strongly affecting R_d. Although features at depths of up to 6 m can be detected with AVHRR, in areas of the bay shallower than 4 m, low reflectance is indicative of low bottom albedo that would indicate dense seagrass

or comparable bottom cover. Areas on the reefs along the southward side of the Keys are deeper and do not allow for ease in distinguishing between grass-covered bottom and deeper water. In all areas, high reflectance may indicate either relatively bare bottom or areas of persistently high turbidity (Philpot 1989); this issue will be discussed later in this paper.

FIELD METHODS

Field ecologists in the area document light attenuation using scalar radiometers that measure photosynthetically-active radiation (PAR, 400–700 nm). We use a Licor 4π PAR sensor for profiles of scalar irradiance (E_0) at 0.25-m increments from 0.25 m (or 0.5 m) depth to the bottom (typically 1.5–2 m). The diffuse attenuation (K_0) is determined from regression of $\ln(E_0)$ against depth, keeping values having $r^2 > 0.9$. (Comparisons of K derived using a PAR cosine collector to K_0 from a scalar collector show negligible differences, so our data should be comparable to that of Phlipps et al. 1995). Comparisons of R_d and K_0 allow the satellite to be used to provide a measure of the effective attenuation, although K_0 has a broader spectral range than R_d from the AVHRR (400–700 nm versus 580–680 nm). Reflectance values to match K_0 values (with $r^2 > 0.9$) are determined by finding the median of the 3×3 block of (nine) pixels around the sampling station within 4 h of overpass. The range of reflectance in the nine pixels provides an approximation of the spatial variance. While the physical relationship between R_d and K_0 is nonlinear, the modest range of K_0 makes a linear approximation appropriate for this region. The relationship between R_d and K_0 can be sensitive to the presence of high concentrations of pigments (Stumpf and Pennock 1991). As the northern and western bay tends to have K_0 driven by higher chlorophyll and pigment concentrations (Phlipps et al. 1995), we determined separate relationships for the eastern and northwestern bay (Fig. 3). The eastern bay relationship applies for chlorophyll below 1 μg l^{-1} and the northwestern bay relationship for chlorophyll over 5 μg l^{-1}. Concentrations of up to 40 μg l^{-1} have been observed in the northwestern bay (Phlipps et al. 1995), with the worst algal blooms observed in 1994.

SEAGRASSES

Bottom coverage of *Thalassia testudinum* in Rankin Lake, Johnson Key Basin, and Rabbit Key Basin was determined using a modified Braun-Blanquet cover-abundance method (Mueller-Dombois and Ellenberg 1974). Coverages for 1991 were obtained by randomly sampling 10 locations per basin from a 0.5-nmi sampling grid. Coverages for
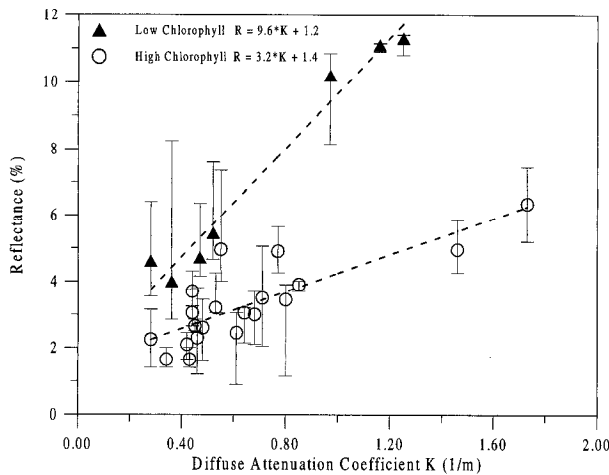
Fig. 3.   Relationship of reflectance and K for the eastern bay (low-chlorophyll) and the northwestern bay (high-chlorophyll). Samples were taken from sites shown in Fig. 1, and four other basins in the bay. The low chlorophyll relationship ($r^2 = 0.97$) was established from 8 d of sampling. The highest attenuation values for both curves came from two basins each, on two separate cruises.

1994–1996 were obtained by systematic random sampling within 30–35 tesselated hexagons per basin. All data were obtained by sampling four 0.25 m² quadrats per station (north, east, south, and west of the vessel). The density values correspond to the following modified Braun-Blanquet cover-abundance scale: 5—cover of more that 75% of the quadrat; 4—50–75% cover; 3—25–50% cover; 2—5–25% cover; 1—numerous stems with less than 5% cover, or scattered with up to 5% cover, 0.5—few stems with small cover; 0.1—solitary, with small cover; 0—not present. The upper four scale values (5, 4, 32) refer only to cover. The lower three scale values are primarily estimates of abundance, that is, number of individuals per species. Frequency of occurrence and density information for each species within a particular basin was calculated using the following formulas: Frequency = (no. of occupied quads)/(total no. of quads); Density = (sum of B-B scale values)/(total no. of quads). The areal extent of each cover class was estimated by kriging the mean station data for each basin (using Surfer software package, Golden Software). With the nominal 1-km spacing of the samples, each 1-m² sample site fell in a different pixel. Reflectances for all pixels with sites in a basin were averaged; the combination of kriging and averaging dampens out the scaling problem between the 1-m² samples with the individual 1.2-km² pixels.

Results

The seasonal means (Figs. 4 and 5) show the general patterns of turbidity and bottom albedo in

Florida Bay and the adjacent offshore region (the area lying outside the park boundary and west of 81°W). In all years, the eastern bay has relatively high reflectance in both winter and summer. This region has consistently had sparse seagrass cover (Zieman et al. 1989; Durako 1996; Hall et al. 1999) and is subject to sediment resuspension, which is enhanced during the winter by increased winds associated with cold fronts. Rabbit Key and Twin Key Basins have the lowest relative reflectance in both winter and summer consistent with the densest seagrass cover (Zieman et al. 1989; Hall et al. 1999) and the least resuspension. The northwestern bay and the offshore region show marked changes between years. The offshore region generally shows low reflectance in 1986–1987, high reflectance in 1988–1991, and low to moderate reflectance after that time. The far western edge of the images, just north of the Pine Keys, shows high reflectance in 1986–1991, and diminishing reflectance after that time. The northwestern bay, which includes Johnson Key, Rankin Lake, etc., begins showing moderately high reflectance in 1988, with substantial increases in reflectance starting in 1992.

During summer, areas of low reflectance correspond to areas reported to have dense bottom cover, and areas of high reflectance generally correspond to sparse bottom cover (i.e., the northeastern bay) (Zieman et al. 1989; Hall et al. 1999). In some areas, such as the channel adjacent to Cape Sable, the high reflectance owes to chronic high turbidity, but this area also does not have seagrass. The years 1985–1987 showed negligible change in summer reflectance. In summer 1988, the offshore region had extremely high reflectance, persisting through 1991. The Pine Keys site began to show lower reflectance in summer, coincident with lower turbidity in winter in that area. In the northwestern bay, high summer reflectance began in 1988, contiguous to the offshore region, particularly around and just west of Johnson Key. Starting in 1991, these areas of high summer (and winter) reflectance expanded substantially. The location of the first phase of increased reflectance corresponds to documentation of the primary seagrass die-offs within Florida Bay between southwest Sprigger and Rankin Lake, including Johnson Key Basin (Robblee et al. 1991; Durako 1994, 1996). In summer 1992, the relatively high reflectance across the northern bay owes to a bias resulting from the anomalously high winds (for the summer) produced by Hurricane Andrew in August, although the areas affected are those which had elevated reflectance in 1991 and 1993. By 1996, the northwestern and central bay, except an area encompassing Rabbit Key and Twin Key Basins, had sum-
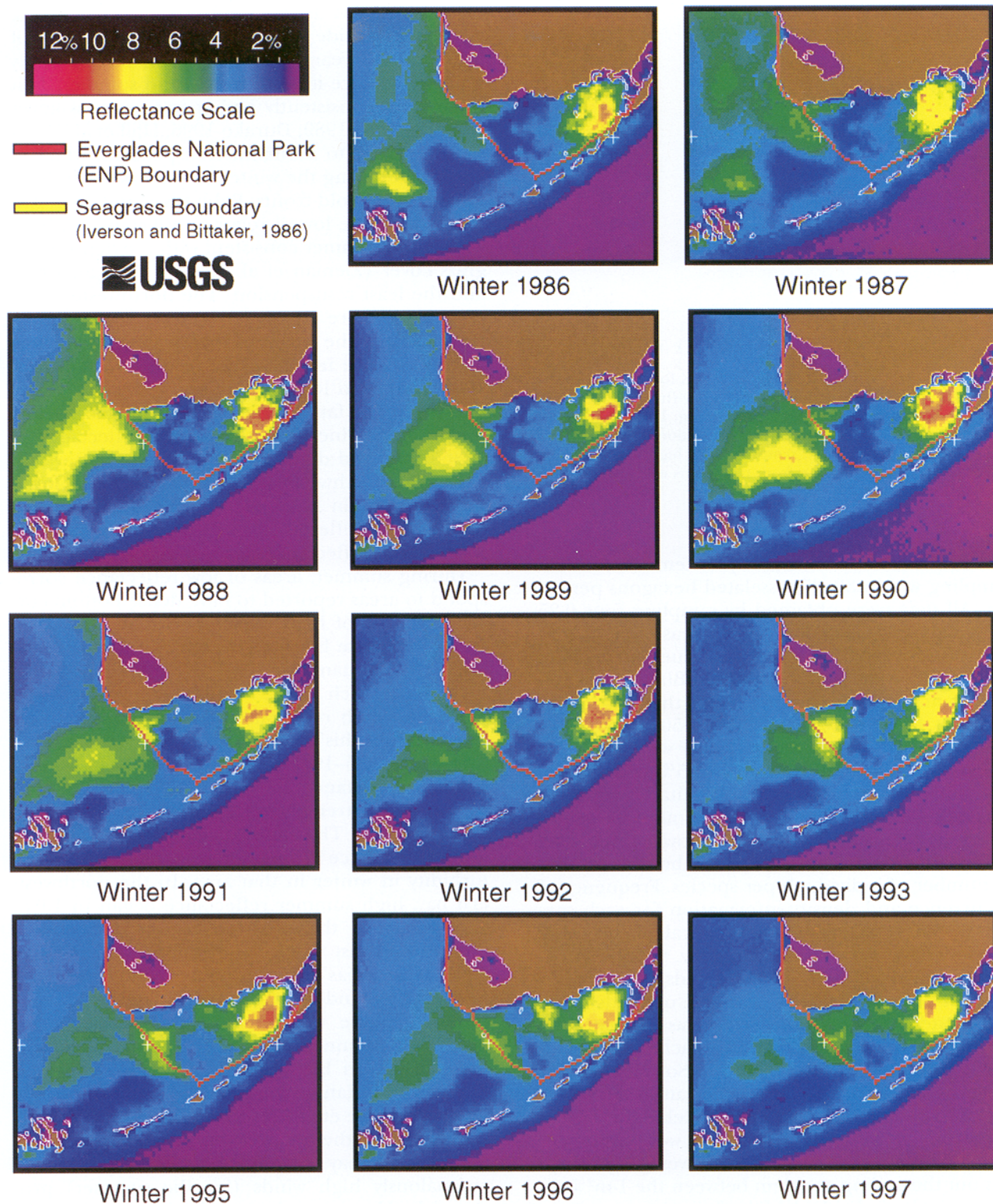
Fig. 4. Winter reflectance means of four months from December of preceding year to March (1995 includes only January 1995 to March), 1986 to 1997. Land is masked in brown, the offshore boundary of Everglades National Park is shown in red. Ticks are at 30' intervals; the center tick is at 25°N, 81°W.
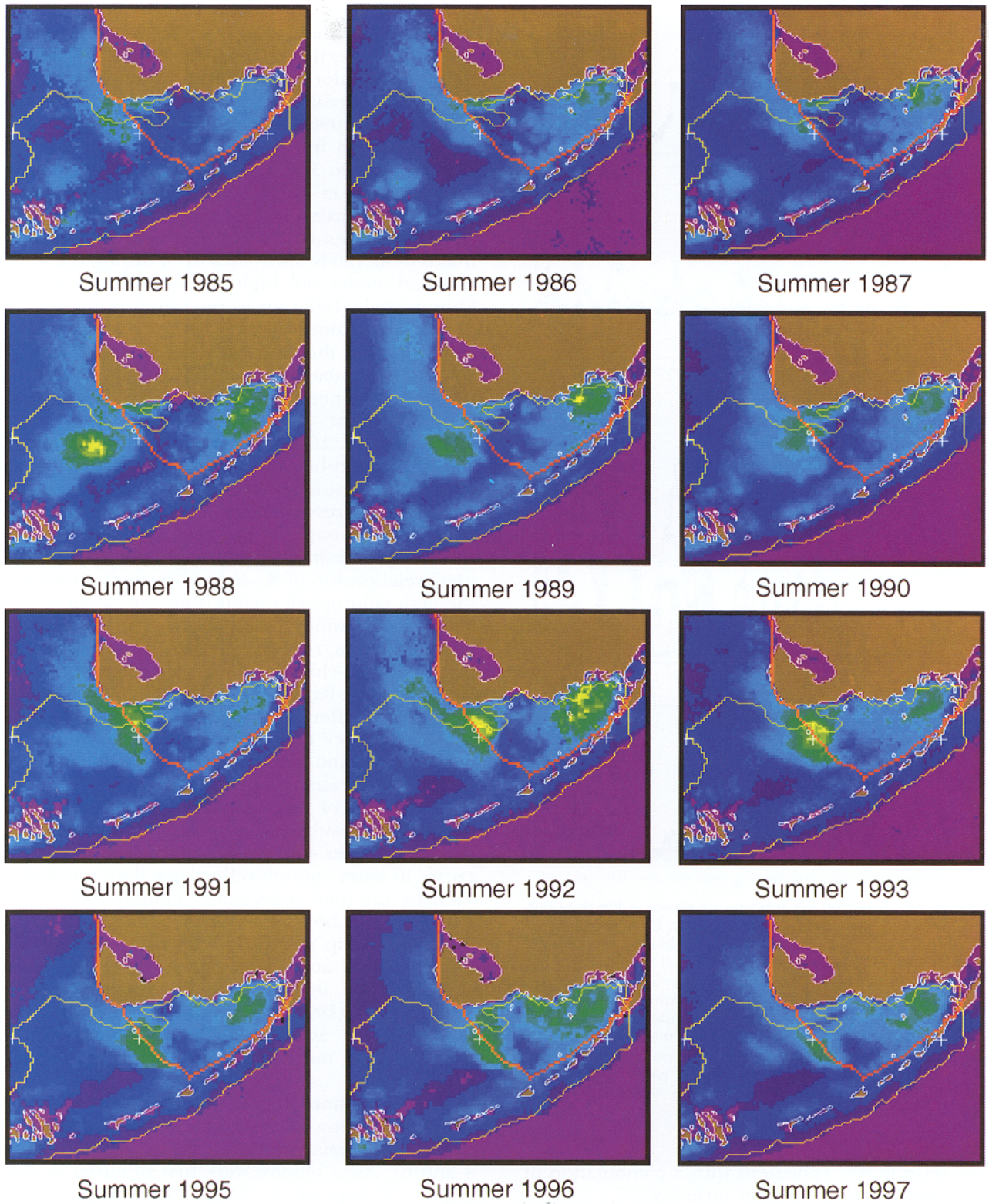
Fig. 5.   Summer reflectance, R_d, means of four months from June to September, 1985 to 1996. Land is masked in brown. The boundary where seagrass is growing (from Iverson and Bittaker 1986) is shown in yellow, and the offshore boundary of Everglades National Park is shown in red. Ticks are at 30' intervals. These images show mostly bottom albedo variations in shallow water, although some turbidity is present.
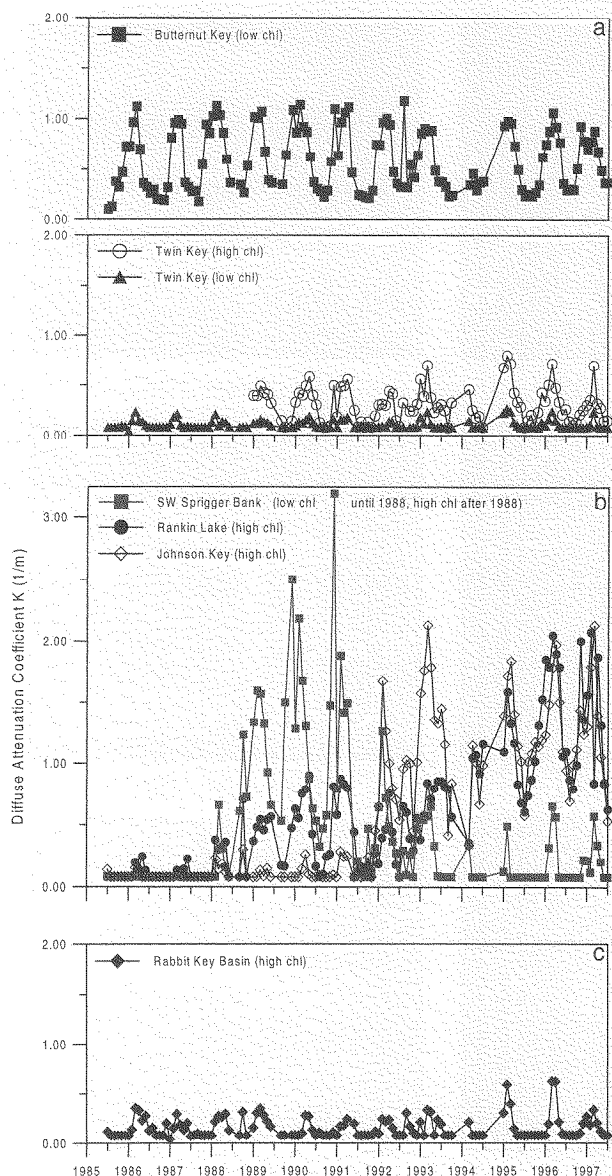
Fig. 6. K_0, based on the relationship shown in Fig. 2, at Butternut Key and Twin Key Basin (a), Rankin Lake, Johnson Key Basin, and southwest Sprigger (b), and Rabbit Key (c). A minimum of 0.08 m^{-1} was determined in the Gulf Stream. Butternut Key uses the eastern (low-chlorophyll) relationship. Rankin Lake and Johnson Key Basin use the northwestern, or high-chlorophyll, relationship. SW Sprigger Bank is given the low-chlorophyll relationship prior to 1988 and the high-chlorophyll one after 1988. While Twin Key may be a low-chlorophyll environment, it has had some blooms, so K_0 has been shown as derived from both relationships subsequent to bloom reports in 1988.

mer reflectances consistent with a combination of bare bottom and persistent turbidity.

An examination of the monthly mean attenuation for 10-km² (nine pixel) areas at different sites (Fig. 6) reveals the details of change in attenuation in the different regions. The relationship between

reflectance and attenuation is influenced by the presence of pigments (Fig. 3). High reflectance areas in the eastern bay, like Butternut Key, have extremely low chlorophyll concentrations (about 0.5 μg l^{-1}; Fourqurean et al. 1993; Phlipps and Badylak 1996; Tomas 1996), resulting in only moderate attenuation even in the winter when reflectance is extremely high. The sparse seagrass cover in this area (Zieman et al. 1989; Hall et al. 1999), and ready resuspension of the carbonate muds (Bosence 1989), result in estimated light attenuation that is moderately low (< 0.3 m^{-1}) during the summer and moderately high (1.0 m^{-1}) in the winter. Phlipps et al. (1995) measured values as low as 0.55 m^{-1} at two stations in the eastern bay in summer 1994; in 1995 they measured attenuation of 0.3–0.5 m^{-1} (unpublished data). The lack of chlorophyll or other pigments in these waters means that only sediment is producing the attenuation (Phlipps et al. 1995), giving these waters a characteristic milky-blue appearance. Twin Key and Rabbit Key Basins represent the extreme of minimal sediment resuspension. These basins have low reflectance throughout the year. Twin Key has had some algal blooms, so although the low-chlorophyll relationship of R_d–K_0 may seem appropriate, the high chlorophyll relationship may be more valid starting in winter 1989. The maximum estimated attenuation remains below 0.5 m^{-1} in most months. High-chlorophyll areas such as Johnson Key Basin and Rankin Lake have high attenuation (1.5–2 m^{-1}) after 1990. The attenuation at these two sites is twice that of Butternut Key; Phlipps et al. (1995) found the same relative difference in their monthly samples from 1994.

Conversion of reflectance to attenuation when the water is relatively clear over a highly reflective bottom involves some uncertainty. The initial increase in water column reflectance does not always increase the total reflectance (Philpot 1989). The correction for bottom reflectance (the constant in the relationship of Fig. 3), can result in overcorrection at low attenuation, giving values that are slightly lower than expected. In contrast with Phlipps et al. (1995), for the Butternut Key region the estimated attenuations during the summer would not be more than 0.1–0.2 m^{-1} below the true values.

In the offshore region at southwest Sprigger, light attenuation appeared to be negligible prior to 1988. A dramatic increase started in 1988 (Figs. 4 and 6). Algal blooms were first reported in this region (Phlipps et al. 1995), so the high-chlorophyll relationship of R_d and K_0 appears appropriate from at least 1988. The area recovered, although not quite to the reflectance range observed in 1986 (Figs. 4 and 6). Chlorophyll concentrations
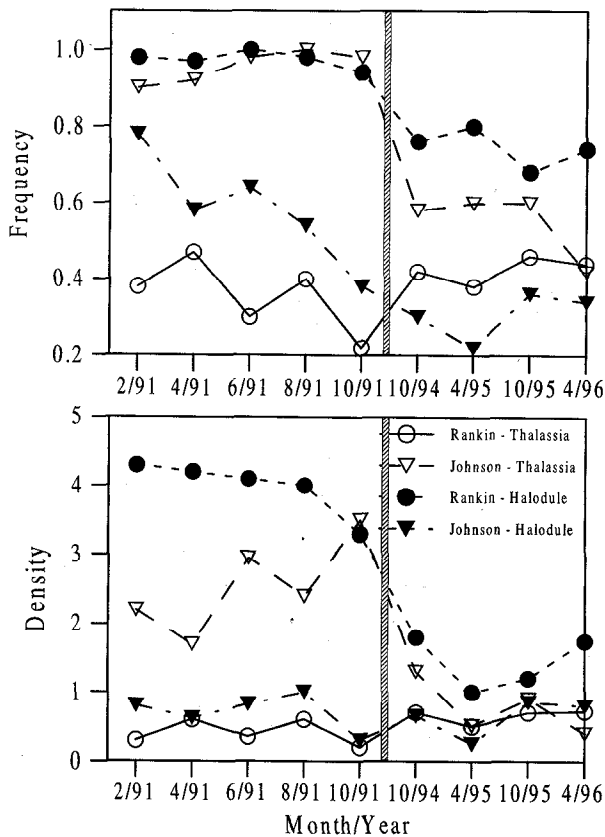
Fig. 7. Frequency of occurrence and Braun-Blanquet (19) density of *Thalassia testudinum* (circles) and *Halodule wrightii* (triangles) in Rankin Lake (open symbols) and Johnson Key Basin (filled symbols). 1991 data were obtained by randomly sampling 10 locations per basin from a 0.5 mi. sampling grid. 1994–1996 data were obtained by systematic random sampling of 30–35 tesselated hexagons per basin. All data were obtained from 0.25-m² quadrats.

in the region still remain somewhat elevated, with concentrations of > 5 μg l^{-1} occurring (Tomas 1996), so moderate attenuation (0.5 m^{-1}) may still be an issue in the winter.

COMPARISONS OF CHANGES IN REFLECTANCE WITH CHANGES IN SEAGRASS COVER

At Johnson Key Basin and Rankin Lake, the timing in changes of winter turbidity correspond to the loss of seagrass. Rankin Lake had an increase in turbidity in the late 1980s, following the die-off of *Thalassia*. This was followed by a slight improve-

TABLE 2. Areas (km²) showing estimated change in bottom cover (between dense and sparse seagrass). The range covers a change in reflectance from 3% in winter and 1.75% in summer to 3.5% in winter and 2.25% in summer. ENP = area of Florida Bay within Everglades National Park.

	ENP	Offshore Region	Total
1986–1991			
Loss	50–70	150–230	200–300
Gain	0	0	0
1986–1997			
Loss	125–200	0–15	125–210
Gain	0	22–50	22–50

ment in water clarity in 1991 that coincided with rapid and widespread colonization by *Halodule wrightii* of the die-off patches in Rankin Lake (Fig. 7). *Halodule* subsequently exhibited dramatic declines in frequency of occurrence and density in Rankin Lake, which corresponded with an increase in turbidity after 1993. Johnson Key Basin was characteristically clear through 1991, consistent with the dense seagrass cover. Extensive die-offs of *Thalassia* and *Halodule* occurred beginning in fall 1991 (Fig. 7), resulting in a rapid increase in turbidity. In area, Rankin Lake and Johnson Key Basin account for most of increased turbidity from 1991 to 1997.

Dense seagrass cover over large areas (> 10 km²) shows low reflectance in summer and winter, and sparse cover shows higher reflectances (Fig. 9). All basins for which there is information on the seagrass cover shows this same pattern, including Rankin Lake, Johnson Key Basin, Rabbit Key Basin (Table 1), and the eastern bay and Twin Key Basin in Zieman et al. (1989) and Hall et al. (1999). Comparison of the Braun-Blanquet data with reflectances suggests that differences of Braun-Blanquet (B-B) from > 4 to < 2 are resolvable in the imagery (Table 1). Changing 2.5 B-B units corresponds to this reduction from $> 50\%$ cover to $< 25\%$ cover at the scale of about 10 km², the areas encompassed by the field program. Both summer and winter show the same response, consistent with low bottom albedo and increased turbidity from resuspension.

To link the reflectance changes to actual changes in seagrass cover, we examined field data from Rankin Lake, Johnson Key Basin and Rabbit Key

TABLE 1. Means ± SD of Braun-Blanquet sites in each basin, and of reflectances for all pixels containing the sample sites.

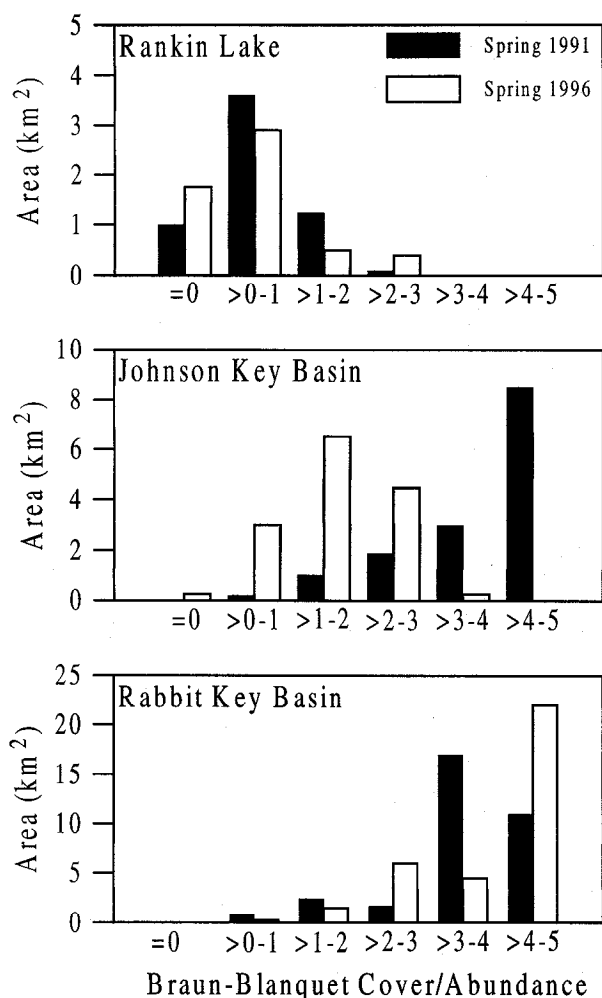|	Winter Reflectance		Summer Reflectance		Braun-Blanquet	
	1991	1996	1991	1996	1991	1996
Rabbit Key	1.4 ± 0.4	2.2 ± 1.3	1.2 ± 0.5	1.2 ± 1.0	3.8 ± 0.7	4.1 ± 1.2
Johnson Key	1.6 ± 0.3	4.5 ± 0.4	1.3 ± 0.3	3.4 ± 0.5	4.3 ± 1.2	1.9 ± 1.0
Rankin Lake	3.6 ± 0.6	6.0 ± 0.4	2.1 ± 0.7	3.7 ± 0.2	2.1 ± 0.8	1.2 ± 1.4

Fig. 8. Distribution of *Thalassia testudinum* bottom cover based on Braun-Blanquet cover-abundance data collected during spring 1991 and spring 1996 in Rankin Lake, Johnson Key Basin, and Rabbit Key Basin. Categories correspond to percentage cover: 4–5, 75–100%; 3–4, 50–75%; 2–3, 25–50%; 1–2, 5–25%; 1, 5%; 0, not present. Rankin had both *Thalassia* and *Halodule* cover in 1991. Johnson and Rabbit were predominately *Thalassia*.
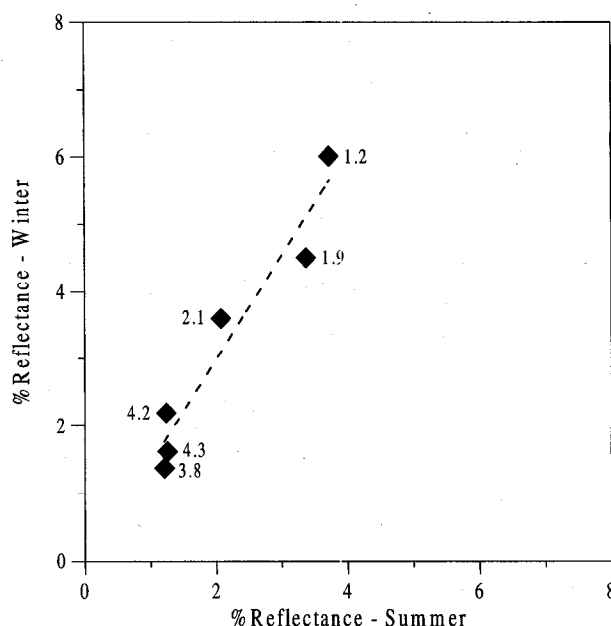

Fig. 9. Comparison of mean summer and winter reflectances from pixels containing Braun-Blanquet sample sites to the mean B-B values for those sites, Rabbit Key Basin, Johnson Key Basin, and Rankin Lake, 1991 and 1996. A minimum of 10 stations are found in each basin.

Basin. Rabbit Key Basin had dense cover over most of the basin in both years, with a shift to most of the basin having 75–100% *Thalassia* cover in 1996. The imagery shows 90% of the basin to have summer reflectances below 2% in 1991. In 1996, 50% of the area had reflectances < 2%, 76% below 3%, and 100% < 4%. The lowest reflectances in the bay at present are found in eastern Rabbit Key Basin and Twin Key Basin. High reflectance occurred from 1991 to 1996 in Johnson Key Basin and Rankin Lake in both summer and winter (Fig. 6). In Rankin Lake, most of the basin was characterized by sparse *Thalassia* cover in 1991 with about 1 km² without any *Thalassia*; however, *Halodule* was present (Fig. 7). By 1996 the area of the moderate cov-

er classes (< 2, < 25%) decreased and the area without *Thalassia* increased to near 2 km² (Fig. 8); although an increase in area of the 25–50% class was observed and reflectance had increased. In Johnson Key, there was also a dramatic loss of the dominant *Thalassia* cover. In 1991 cover class 5 (75–100% cover) was predominant, covering most of the basin (> 8 km²); by 1996 cover class 2 (5–25% cover) predominated but over 2 km² of the basin had less than 5% *Thalassia* cover (cover class 1). In the imagery, 100% of the basin area had summer reflectance < 2% in 1991, but in 1996, 100% of the area had reflectances > 3%.

Discussion

The imagery set shows that the increase in turbidity began in the offshore region in late 1987. In summer 1987, when the first evidence of *Thalassia* die-off appeared in Florida Bay (Robblee et al. 1991), no change in reflectance from previous summers was evident from the imagery. Robblee et al. (1991) state that the initial die-offs occurred most rapidly in the fall and spring, with rapid declines between August and October. In winter 1988, resuspension throughout the offshore region was far more extensive than in the previous winters, suggesting an extensive loss of bottom cover between September and December, consistent with a fall decline. The continuation of high reflectance in summer 1988 in the same region, without in-
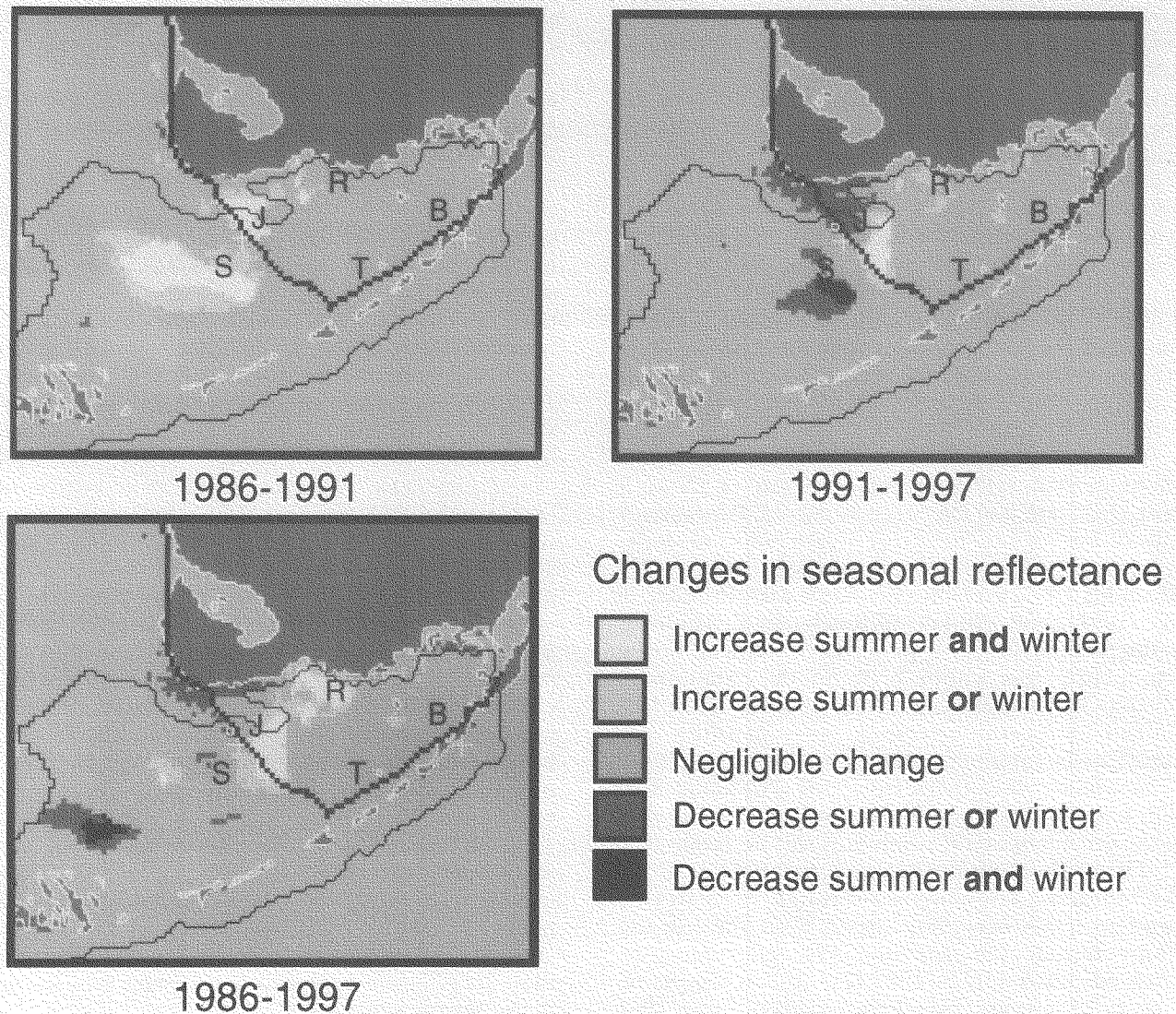
1986-1991   1991-1997

Changes in seasonal reflectance

☐ Increase summer **and** winter

☐ Increase summer **or** winter

☐ Negligible change

■ Decrease summer **or** winter

■ Decrease summer **and** winter

1986-1997

Fig. 10. Seasonal differences between 1986, 1991, and 1997. Winter changes of 3.25% correspond to a change in attenuation (high chlorophyll) of 1.0 m^{-1}; summer changes of 2.0% correspond to an estimated Braun-Blanquet change of 2.5. An increase in reflectance in both winter and summer implies loss of bottom cover that would control resuspension; a decrease implies the conversion of bare bottom (or sparse seagrass) to dense cover. The offshore boundary of Everglades National Park is marked with the heavy line, and the Iverson and Bittaker (1986) seagrass boundary is marked with the thin line (see Fig. 5). S = SW Sprigger, J = Johnson Key Basin, R = Rankin Lake, T = Twin Key Basin, and B = Butternut Key.

creased reflectance in other areas of the Bay (that could allow an explanation of anomalously high winds), indicates that loss of bottom cover was real. By winter 1989, the region of high turbidity had spread over the maximum area of the offshore region.

While studies within the bay show a continued increase in turbidity and a decline in seagrass, this study shows considerable complexity in the spatial distribution of reflectance. The offshore region had an increase in reflectance through to 1991 (Fig. 10), then showed decreased reflectance and attenuation, with indications of some increase in

bottom cover (Figs. 4 and 10). Within ENP, the bay has remained stable in the south and east, has had continued high reflectance in the north-central bay, and has shown some improvement in the mud bank area in winter 1996 and 1997 in the northwest bay. In summer 1997, reflectance decreased on the banks between Cape Sable and Johnson Key Basin. The phenomenon has persisted into winter 1998, when we identified it as an extensive *Halodule* meadow. The imagery confirms changes in turbidity after 1991 as was found by Boyer et al. (1997), and greatly clarifies the timing, magnitude, and distribution of turbidity changes.

From our sites in 1991 and 1996 we have determined that a change of 2.5 B-B corresponds to about 3.25% reflectance in winter and 2% in summer, based on the difference in means between the dense sites (Rabbit Key in 1991 and 1996; Johnson Key Basin in 1991) and the sparse sites (Rankin Lake in 1991 and 1996; Johnson Key Basin in 1996). To assess change in cover we required this condition to be met for both seasons. If the reflectance increased > 3.25% in winter and > 2% in summer, we infer that the site changed from dense cover to sparse or no cover. A decrease in reflectance of the same amount indicates the converse (Fig. 10). As we have limited comparative data for intermediate cover densities, we have not considered intermediate changes.

In the first stage of the die-off through 1990, Robblee et al. (1991) estimated 40 km² of *Thalassia* were lost, and 230 km² were impacted. We estimate 50–70 km² of loss or severe degradation of dense seagrass meadows (of all species) within ENP through 1991, a result consistent with Robblee et al. (1991), and 200 km² of loss by 1997. These results provide the first quantitative estimate of the cumulative loss within ENP. Subtle variations in change cannot be evaluated at present as we lack information on intermediate cover densities, and small beds cannot be detected. Conversion from *Thalassia* to other species (e.g., to *Halodule* in Rankin Lake in 1991) cannot be resolved with this sensor—greater spectral resolution will be required.

The offshore region had an estimated loss of 200 km² of dense bottom cover through 1991. In contrast to losses occurring within ENP, the loss did not continue after that time. The reflectances decreased sufficiently by 1997 (Fig. 10) to suggest recovery of bottom cover had occurred. From 1986 to 1997 the cumulative change from dense cover to bare bottom was negligible (about 15 km²), and 50 km² showed conversion to apparently dense seagrass cover, mostly by the Pine Keys. The low reflectance north of Vaca Key (Marathon), which corresponds to an extensive *Syringodium* meadow, was reported to be exclusively *Syringodium* by Iverson and Bittaker (1986). The expansion of this low-reflectance feature westward toward Big Pine Key suggests that the *Syringodium* meadow has expanded. The result is a change in the configuration of seagrass meadows in the offshore region, with a slight loss of dense cover west-southwest (WSW) of Cape Sable (Fig. 10, 1986–1991), and new dense cover in the western region. Much of the region WSW of Cape Sable, while having a decrease in reflectance, has not returned to the same low reflectances as observed in summers of 1985–1987.

Are alternative explanations to seagrass loss available for the changes in reflectance in the off-shore region? Several could be considered: increased resuspension during 1988–1991; presence of non-seagrass bottom algae in 1985–1987; and dramatic changes in water color. The water depth in that region is comparable to the water depth of the current *Syringodium* meadow, 2–3 m (up to 10 feet), so seagrass could be observed by satellite in this area. Increased resuspension would need to occur in both summer and winter 1988–1991 to explain the patterns. Resuspension during the summer requires a wind event that would affect only the offshore, and not the bay or reef tract. A tropical storm is the appropriate candidate, but none occurred during this time. Even Andrew in 1992 did not affect summer averages in the offshore area. For a non-seagrass cover like drift algal to produce the observed reflectances, the algal would have had to persist in the same region in both winter and summer 1985–1987, succeed in reducing resuspension, then disappear in 1988. The persistence and reduction in resuspension seem unlikely. The last option would be the presence of pigments that strongly absorb light (thereby reducing reflectance) in 1985–1987, with these pigments diminishing in 1988. However, in the bay, chlorophyll blooms do not dominant the reflectance signal from sediments. It is unlikely that blooms would occur in the offshore region. These blooms would need to be remarkably persistent, remaining in the same area from 1985 to 1987. The other pigment suite—dissolved organic pigments—that can decrease reflectance has a significant source only in the Ten Thousand Islands area north of Cape Sable, far removed from the area of concern. These alternatives are less convincing than the scenario of changing reflectance by losing dense seagrass meadows.

Iverson and Bittaker (1986) estimated 2,900 km² of seagrass coverage in the late 1970s in the offshore region between the seaward limit of seagrass (marked on Figs. 4 and 5) and the 2 m contour (which is at about 81°W). The region that had increased reflectance between 1986 and 1991 contains approximately 48 of their sample sites. Of these, 41 had some type of seagrass cover, with 23 having *Thalassia*, 15 having *Syringodium*, and 14 having *Halodule* (many sites were mixed). While hypersalinity has been suggested as one of the primary co-stressors in Florida Bay, the offshore region would have had normal marine salinity (based on data from the western part of Florida Bay; Boyer et al. 1997). The indication is that disease or other factors (sulfide development in the substrate, etc.) unrelated to salinity may have started the die-off. *Labyrinthula* disease in *Thalassia* has been suggested as a key factor in the die-offs (Robblee et al. 1991; Durako and Kuss 1994). As *Thal-*

assia was a significant part of the offshore region, disease may have caused the apparent decline in bottom cover in the offshore region in 1988, and light limitation from high turbidity may have caused the subsequent declines in other species. We should note, however, that the area of improvement in the Pine Keys area also had *Thalassia* at six of nine sites in Iverson and Bittaker's (1986) study. Additional investigation would be required to determine the presence of *Thalassia* or conversion to other species, like *Syringodium filiforme*.

Thalassia appears to require a minimum of 20% of the light incident on the water's surface (Gallegos and Kenworthy 1996); this corresponds to K_0 of 1.1 m^{-1} in 1.5 m of water, 0.8 m^{-1} in 2 m, and 0.5 m^{-1} in 3 m. The *Syringodium* meadow north of Vaca Key is located in 2–3 m of water. *Syringodium* can tolerate lower light than *Thalassia* (Iverson and Bittaker 1986). A significant question remains about the dramatic changes in the offshore region, in particular what caused the decrease in reflectance in the southwest Sprigger region starting in 1991. Reexamination of the Iverson and Bittaker (1986) sites would be essential to this purpose.

Conclusions

The AVHRR imagery reveals new spatial and temporal detail on turbidity and changes in bottom cover on the Florida Bay region over the past 12 yr. The imagery confirms the existing view that water clarity in the Bay was generally excellent prior to the die-offs. The one exception is the eastern bay, which has had winter resuspension events since at least 1985. The severe turbidity in winter has developed and expanded through the northwest bay, including Johnson Key Basin and Rankin Lake areas. An extensive region of low-reflectance water in the northwestern bay has disappeared, with a gradual expansion of high reflectance in summer from 1987 to 1996. The increase in reflectance in both winter and summer during this time indicates a loss of 200 km^2 of dense seagrass in the offshore area, which preceded most of the extensive seagrass die-offs in the bay. The offshore region has shown subsequent reductions in reflectance, indicating some recovery of bottom cover. North of Marathon, a *Syringodium*-dominated bed may be expanding westward toward Pine Keys.

An appropriate next step is to convert the reflectances to seagrass cover through the Braun-Blanquet values or other quantitative measurements (e.g., biomass, short-shoot density, etc.; Zieman et al. 1989; Hall et al. 1999), and to relate the cover values to attenuation or turbidity in the overlying water. This information will provide the details to refine use of the imagery in characterizing seagrass change in the bay.

The attenuation coefficients determined here provide a good measure of light attenuation in the bay. The influence of chlorophyll on the relationship between R_d and K_0, however, must be addressed with ancillary data. The northern and western relationship occurs with measured chlorophyll from 4 to 12 $\mu g\ l^{-1}$, although concentrations of up to 40 $\mu g\ l^{-1}$ have been reported, with 1994 being the worst year for algal blooms (Phlipps and Badylak 1996; Tomas et al. In press). Identification of basins that tend to have high chlorophyll is critical, although in the future, examination of relative pigments with ocean color sensors, such as SeaWiFS, will permit determination of K_0 solely with the imagery without the need for geographic constraints.

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